

High-Latitude Stratospheric Sensitivity to QBO Width in a Chemistry-Climate Model with Parameterized Ozone Chemistry

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In a pair of idealized simulations with a simplified chemistry-climate model, the sensitivity of the wintertime Arctic stratosphere to variability in the width of the quasi-biennial oscillation (QBO) is assessed. The width of the QBO appears to have equal influence on the Arctic stratosphere as does the phase (i.e. the Holton-Tan mechanism). In the model, a wider QBO acts like a preferential shift toward the easterly phase of the QBO, where zonal winds at 60°N tend to be relatively weaker, while 50 hPa geopotential heights and polar ozone values tend to be higher.

1 Motivation

18 The quasi-biennial oscillation (QBO) is the dominant mode of meteorological variability in the
19 equatorial lower stratosphere. The QBO in zonal winds has been observed since the 1950s [e.g.,
20 Graystone, 1959; Reed, 1960; Ebdon, 1960] and is characterized by an alternation between
21 easterly and westerly winds in the equatorial stratosphere, with a period of approximately 27
22 months. The maximum amplitude of the QBO in zonal winds is approximately 20 m s^{-1} in the
23 lower stratosphere and 5 m s^{-1} near the stratopause. (See Baldwin et al. [2001] for a detailed
24 review of the QBO phenomenon.)

26 The influence of the QBO on the dynamics of the Northern Hemisphere (NH) polar stratosphere
27 is well recognized. Holton and Tan [1980] showed that, during NH winter season, high-latitude
28 50 hPa geopotential heights were relatively lower and zonal winds were relatively weaker during
29 the easterly phase of the QBO as compared with the westerly phase. Planetary waves are only
30 able to propagate when the zonal mean flow is westerly and below a critical value [Charney and
31 Drazin, 1961]. During the easterly phase of the QBO, the zero wind line (separating
32 stratospheric easterlies from westerlies) is pushed north of the equator, confining planetary wave
33 propagation to Northern middle and high latitudes. McIntyre and Palmer [1983, 1984] showed
34 that planetary wave “breaking” at high latitudes induces a drag on the mean flow, weakening
35 westerly winds.

37 Previous studies have noted that the QBO appears to be approximately symmetric about the
38 equator, with zonal wind magnitudes decaying away from the equator following a Gaussian
39 distribution with a half-width of $10\text{--}12^\circ$ [Baldwin et al., 2001]. The width variation of the QBO

is examined in Figure 1. High-resolution zonal wind data [Kalnay et al., 1996] suggest that the latitudinal extent of the zonal wind QBO varies from one cycle to the next. The pale (dark) lines in Figure 1 show latitudes where the correlation coefficient between zonal winds at 30 hPa at Singapore (1°N, 104°E; <http://geo.fu-berlin.de/met/ag/strat/producte/qbo/index.html>) and analyzed winds exceeds 0.5 (0.8); each pair of lines corresponds with a complete QBO cycle, beginning with the easterly phase, between 1997 and 2007. The region where the correlation coefficient exceeds 0.8 extends from 11–17°N to 7–15°S. Considering the dependence of the latitudinal distribution of stratospheric zonal winds on planetary wave propagation, variation in the width of the zonal wind QBO may affect high-latitude dynamics, and thus the potential for polar ozone depletion.

This study investigates the high-latitude stratospheric response to a change in the width of the QBO. A pair of idealized chemistry-climate model (CCM) simulations, as described in section 2, is used to investigate the following questions: Would a broader QBO and a poleward shift of the zero wind line affect the strength of the NH polar jet, as described by the Holton–Tan relation? Chemistry–transport model studies [e.g., Hadjinicolaou et al., 2002, 2005; Jrrar et al., 2006] have highlighted the importance of meteorological variability on recent trends in Arctic ozone. Does variation in the width of the QBO affect polar ozone concentrations? Section 3 describes the experimental results, focusing on the NH high latitudes in mid-winter. Section 4 summarizes the findings and discusses their implications for the interpretation of polar stratospheric ozone data.

2 Experimental Design

Two 15-year simulations with version 4.5.1 of the UK Met Office Unified Model (UM) are examined in this work. Braesicke and Pyle [2003, 2004], Pyle et al. [2005], Braesicke et al. [2006], M. M. Hurwitz et al. (submitted to Journal of Climate, 2010b) and others have successfully used this model to assess stratospheric sensitivity to various climate forcings and to better understand stratospheric chemistry–climate interactions. Version 4.5.1 of the UM CCM has $3.75^\circ \times 2.5^\circ$ horizontal resolution and 64 vertical levels, with ~ 1.3 km resolution in the stratosphere. The climate model is coupled non-interactively with the Cariolle and Déqué [1986] parameterized ozone chemistry scheme. The chemical module contains a cold tracer used to mimic the impact of polar stratospheric clouds (PSCs) on polar ozone. The simulations use a monthly mean AMIP II sea surface temperature (SST) climatology with a repeating annual cycle (see <http://www-pcmdi.llnl.gov/projects/amip/AMIP2EXPDSN/BCS/bcsintro.php>). Late 20th century greenhouse gas concentrations are prescribed and remain constant throughout the simulations. Climate variability associated with the solar cycle and volcanic aerosols is not considered.

Since a non-orographic gravity wave drag scheme [e.g., Warner and McIntyre, 2001] is not implemented, the UM is not able to generate an internal QBO. In this model configuration, however, observed tropical zonal winds are used to nudge the model toward the observed QBO. In the present study, the UM is nudged with data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) global reanalysis [Kalnay et al., 1996], which is interpolated onto model pressure levels. The nudging is applied using a Gaussian weighting function centered at the equator, with relatively weaker nudging at higher latitudes. For the control run, called QBO–A, tropical stratospheric zonal winds are nudged

within an 8° half-width. The nudged QBO applied in experiment QBO-A is expected to compare well with zonal wind and ozone observations. A broader QBO (QBO-B) is simulated by approximately doubling the half-width of the QBO forcing to 15° .

3 Results

Figure 2 shows a timeseries of equatorial zonal mean zonal wind in control simulation QBO-A, and confirms the implementation of the nudged, observed QBO in the model. Throughout the 15-year simulation, there is good correspondence of the magnitude and periodicity of zonal mean zonal winds in QBO-A with observations (see <http://geo.fu-berlin.de/met/ag/strat/producte/qbo/index.html>). Near the equator, the periodicity and the width of the ozone QBO in simulation QBO-A also corresponds reasonably with observations [not shown; see Hurwitz, 2008].

In the NH polar stratosphere, zonal winds are more than 20 m s^{-1} stronger in QBO-A than in QBO-B; a two-tailed t-test found the January mean zonal winds at 60°N , 10 hPa in the two simulations to be distinct at the 99% confidence level. In the tropical stratosphere, there is a wider zone of stratospheric easterlies when the QBO forcing is broader.

Relative weakening of the NH polar jet in QBO-B, as compared with QBO-A, corresponds with a weakening of the meridional temperature gradient in the NH stratosphere. Thus, it follows that January mean QBO-B – QBO-A temperature and geopotential height differences are positive (greater than 15 K and 250 m, respectively) at polar latitudes. The pattern of 50 hPa QBO-B – QBO-A geopotential height differences is illustrated in Figure 3. At high latitudes in mid-

winter, QBO-B – QBO-A geopotential differences (~200 m) are comparable to differences between the easterly and westerly phases of the QBO found by Holton and Tan [1980].

Because the modeled NH polar region is warmer in mid-winter, less PSCs can form and so less chemical ozone depletion can occur. Therefore, January mean ozone mixing ratios in the high latitude lower stratosphere are on average 0.6 ppmv higher in QBO-B than in QBO-A [see Figure 4 and Hurwitz, 2008]. QBO-B – QBO-A total ozone differences increase between October and February, then decrease in March; ozone differences are insignificant during the NH summer season. Changing the width of the QBO forcing has little impact on total column ozone in the tropics.

Scatter plots of January total column ozone at 80°N versus zonal mean zonal wind at 10 hPa, 60°N (where zonal mean zonal wind at 60°N is used as a proxy for the strength of the NH wintertime polar vortex) evaluate the interaction between dynamics and chemistry in the high latitude stratosphere [Braesicke and Pyle, 2004; Braesicke et al., 2006]. Experiments QBO-A and QBO-B are clearly distinguished: in Figure 4, Januaries in experiment QBO-B have relatively higher polar ozone values (centered roughly at 475 DU) and weaker zonal winds (generally, less than 30 m s^{-1}) than do Januaries in QBO-A. The majority of QBO-A Januaries are in the high zonal wind and low ozone regime. However, Januaries in QBO-A have a broader range of zonal wind and ozone values than do Januaries in QBO-B. In QBO-A, zonal winds range from -5 m s^{-1} (indicative of an extreme disruption of the polar vortex) to 50 m s^{-1} ; total ozone values range from approximately 360 to 450 DU. In both experiments, there is a relatively

tight relationship between zonal mean zonal wind and ozone. The two linear regressions have similar slopes.

4 Discussion

Two 15-year simulations with a simplified chemistry–climate model were used to test the stratospheric sensitivity to a change in the width of the QBO. A nudging technique was used to force near-equatorial winds to resemble observations (see Figure 2). The half-width of the QBO nudging in a control simulation (QBO–A) was doubled in experiment QBO–B. Near the equator, zonal winds were nudged toward the same climatological values in both experiments. Thus, zonal wind and ozone differences were negligible in the tropics. Differences in the two Gaussian functions forcing the QBO appeared poleward of approximately 20°.

The strength of the NH polar stratospheric jet was affected by the change in width of the QBO. Broadening the QBO forcing tended to disrupt the jet (see Figure 4) though the extent of this disruption varied from year to year. On average, the zero wind line shifted poleward. According to the Holton–Tan mechanism [1980], this poleward shift would strengthen planetary wave forcing at high latitudes and decelerate the westerly zonal winds. That is, broadening the QBO forcing has the same effect on high-latitude dynamics as does a preferential shift toward the easterly phase of the QBO. At NH high latitudes, mid-winter geopotential height and ozone differences were generally positive, corresponding with the QBO–B – QBO–A wind differences described above (see Figure 3).

While recent work has examined both the behavior of an internally-generated QBO in a CCM [Tian et al., 2006] and the impact of the QBO on the extra-tropics [e.g., Hampson and Haynes, 2006], this study is the first to have assessed the stratospheric sensitivity to a change in the characteristics of the QBO itself. This study finds that a relatively broader QBO leads to increased high-latitude ozone concentrations in mid-winter, whereas a narrower QBO leads to lower ozone concentrations in the same region. Since meteorological conditions affect middle and high-latitude ozone variability [Hadjinicolaou et al., 2002, 2005], polar ozone may be affected by changes in climate, such as the widening of the tropical belt [Seidel et al., 2008]. However, the results of this study suggest that hugely altering the QBO (i.e. doubling its width) does not affect the compactness of the relationship between polar ozone and vortex strength (see Figure 4).

Given the significant decrease in zonal winds at Northern high latitudes in January when the QBO forcing is broadened, it would be interesting to investigate the effects of other changes in the QBO on the NH polar stratosphere in a fully-coupled CCM. Two possible parameters to be varied are the magnitude of the wind oscillation (perhaps enhancing the northward shift in the zero wind line) and the QBO period (perhaps affecting the timing and/or strength of the Holton-Tan effect).

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Captions

Figure 1: Latitudes where the correlation coefficient between 30 hPa zonal winds measured at Singapore (1°N , 104°E) and zonal winds from the $1^{\circ} \times 1^{\circ}$ NCEP/NCAR reanalysis exceeds 0.5 and 0.8. The five pairs of lines correspond with QBO cycles that occurred between 1997 and 2007.

Figure 2: Timeseries of equatorial zonal mean zonal wind [m s^{-1}] in simulation QBO-A.

Figure 3: QBO-B – QBO-A mean NH 50 hPa geopotential height differences [m] in January. The white contour line denotes zero difference between the two simulations.

Figure 4: Scatter plot of zonal mean zonal wind at 60°N and 10 hPa [m s^{-1}] versus zonal mean total column ozone at 80°N [DU] for each January, for the QBO-A (blue points) and QBO-B (turquoise points) simulations. The lines of best fit are shown in black.

Figures

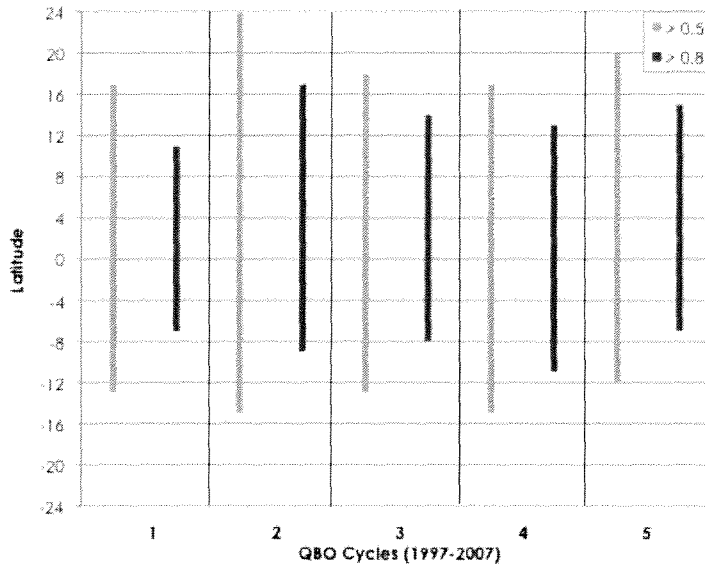


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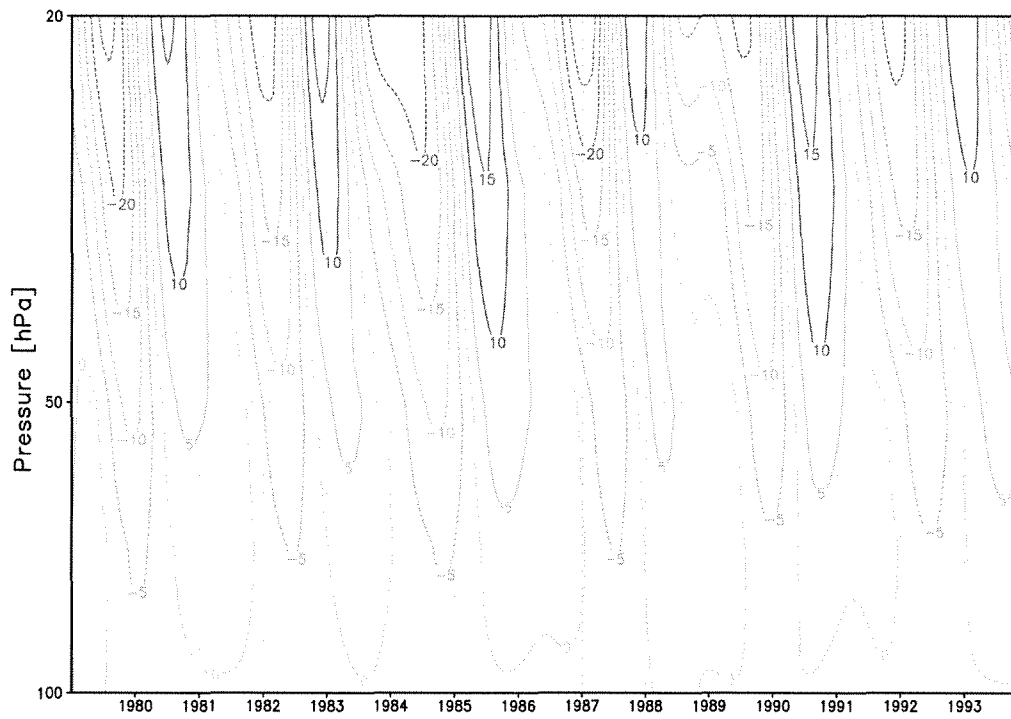


Figure 2: Timeseries of equatorial zonal mean zonal wind [m s^{-1}] in simulation QBO-A.

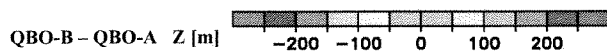
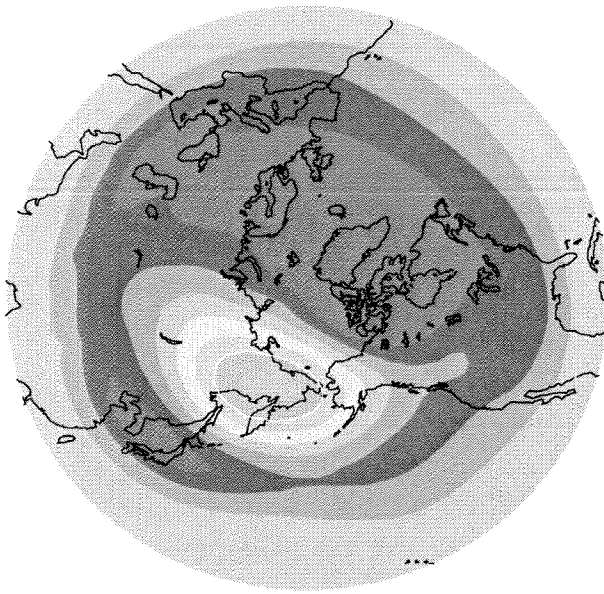


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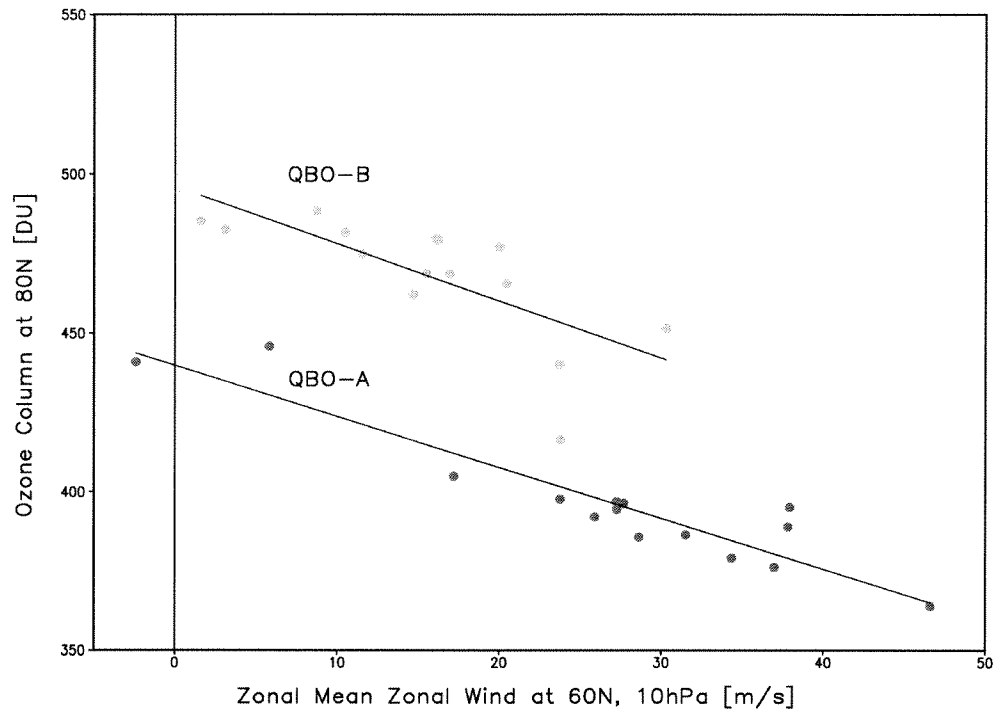


Figure 4: Scatter plot of zonal mean zonal wind at 60°N and 10 hPa [m s^{-1}] versus zonal mean total column ozone at 80°N [DU] for each January, for the QBO-A (blue points) and QBO-B (turquoise points) simulations. The lines of best fit are shown in black.